SCIENCE FOR GLASS PRODUCTION

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OPTICAL INTERFERENCE SYSTEM FOR CONTROLLING FLOAT-GLASS RIBBON THICKNESS AT HOT STAGES OF PRODUCTION

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A new multichannel system for technological control of float-glass thickness at the beginning of the annealing furnace based on the interference principle of thickness measurements is described. The system provides for continuous control of float-glass ribbon thickness simultaneously at several points (from 1 to 10) in real time with an error of 5 μm.

The float-process is currently the most effective method for high-quality sheet glass production. One of the trends in improving the float process consists in constant monitoring of glass ribbon parameters at the stage of its formation. A significant aspect of this monitoring is measuring the glass ribbon thickness beyond the edge-forming machines at the end of the float-tank or at the beginning of the annealing furnace.

Such measurements are needed primarily for effective control of the production line when changing from one particular thickness to another. This transition inevitably involves glass melt losses, which are proportional to the duration of the transition. In the case of traditional monitoring of the glass ribbon thickness at the cold end of the line, substantial time losses are caused by the time lag between the operator's actions in the hot zone and obtaining information on the results of these actions at the cold end of the line. Such delay is equal to the time it takes the glass ribbon to move from the molding zones (edge-forming machines) to the control zone. For typical process parameters this time is about 30 min. The ribbon thickness control in front of the annealing furnace (immediately after the edge-shaping machines) significantly reduces the time lag in the operators' response to this delay and thus reduces time and glass losses in such transition. Furthermore, such control allows for more precise adjustment of ribbon thickness to the bottom boundary, which also contributes to saving glass melt.

The system of glass thickness control in the hot zone has to meet stringent requirements: It has to operate continuously during the full service life of a float-glass production line (about 10 years) and be stable in transition from one thickness to another, even at the moment of a very fast change of the glass ribbon thickness. To control the cross-section profile of a glass ribbon, the system should ensure measurements of thickness at various points across the ribbon. Servicing the system should not be complicated, and at the same time it should be protected from damage during such emergencies as breaking of the glass ribbon.

The multichannel optical system for technological control of glass ribbon thickness in the hot zone developed at the Institute of Microstructure Physical of the Russian Academy of Sciences satisfies the above requirements.

At present, the thickness of a float-glass ribbon is mainly controlled using triangulation optical methods, which are based on slanting illumination of glass with a collimated light beam and measuring the lateral shift between the beams reflected from the upper and the lower glass surfaces (Fig. 1). In methods known as "moire methods" a beam projected on glass has a complex structure, which provides for more accurate measurement of the shift between the beams. Measuring systems based on the triangulation principle are offered by Grenzebach Maschinenbau GmbH and Beta Instrument Europe Companies [1, 2].

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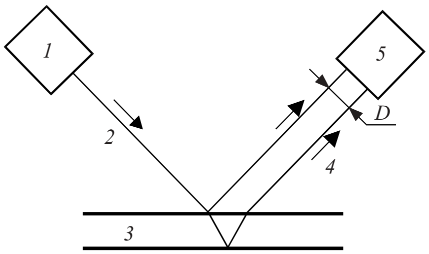

Fig. 1. System for measuring glass thickness by the triangulation method: *1*) light source, *2*) incident beam; *3*) glass; *4*) reflected beams; *5*) recording device; *D*) distance measured between reflected beams proportional to glass thickness.

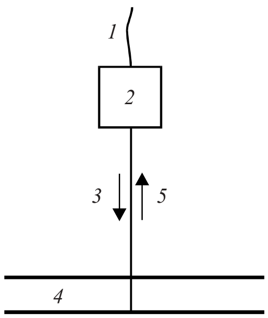

Fig. 2. System for measuring thickness by the interference method (the paths of the incident and reflected beams coincide; the interference image is processed in a remote measuring block connected with the optical head by a fiber-optic cable): *1*) fiber-optic cable; *2*) optical head; *3*) incident beam; *4*) glass; *5*) reflected beams.

An alternative approach to measuring glass thickness is based on observation of the interference image created by light beams reflected from the upper and lower surfaces of the glass ribbon (Fig. 2). This image is determined by the optical pathlength difference of interfering beams. Under normal incidence of the probing beam on a glass ribbon, this difference is equal to twice the optical thickness of the glass, i.e., twice the product of the glass thickness by its refractive index.

The optimum, although not the only possible, geometry for interference measurement of glass ribbon thickness is the normal incidence geometry, in which the probing beam is oriented perpendicularly to the glass surfaces. In normal incidence geometry, the interference method has significant advantages over the triangulation method. In contrast to triangulation measurements, interference measurements are virtually free from errors related to nonuniform thickness of the glass ribbon (non-parallel lower and upper glass surfaces) or air turbulence in the space between the glass and the gage head. Nonuniform thickness of the glass ribbon In triangulation measurements results in a measurement error on the order of αL (α is the wedge angle; L is the path between the reflection point and the gage head). Because of L the measurement error can become significant even with low values of α. In interference measurement, nonuniform thickness leads to a negligibly small error $\sim \alpha^2$, which does not depend on the distance between the glass and the gage head. This is especially important for reliable work of the measuring system in transition from a certain glass thickness to another, when deviations of glass surfaces from parallel can be significant.

Air turbulence above the glass ribbon may arise due to inhomogeneity of temperature inside the annealing furnace, or in supplying air from outside. In triangulation measurements, air turbulence leads to a random error in measuring thickness due to refraction of reflected beams on random heterogeneities of the turbulent medium. The said error grows with increasing path of the beams in the turbulent medium. This makes it necessary to place the gage heads either very near the glass ribbon in the high-temperate zone, or beneath the glass ribbon, where turbulence is weaker, but there is a risk of the heads being damaged in the case of a ribbon break. In interference measurements, both reflected beams pass via the same inhomogeneities of the medium; therefore, their pathlength difference does not change, and no error arises in measuring thickness. The low sensitivity to nonuniform thickness of the glass ribbon and to air turbulence makes it possible to place the gage heads of the interference system at a substantial distance from the glass ribbon, outside the high-temperature zone. This ensures mild temperature conditions for the gage heads and ease of their adjustment and servicing, as well as prevents damage of the gage heads from the glass ribbon fragments in breaking.

Thus, the interference principle of measuring glass ribbon thickness has substantial advantages compared to the triangulation method, especially for high-temperature measurements. However optical interferometers are traditionally considered to be very sensitive to mechanical and thermal effects; therefore, they are not applicable under hot-production conditions. The recent progress in laser and fiber optics recently has made it possible to develop new noise-resistant interference measurement methods, which can be used under the most severe industrial conditions (RF Patents Nos. 2141621 and 2147728).

The optical interference system developed by us is intended for continuous control of float-glass thickness in the beginning of the annealing furnace (zone A). The system consists of four main blocks: measuring blocks, optical heads (whose number is equal to the number of measurement channels), a fiber-optic cable, and a control block (Fig. 3).

The measurement block *1* contains all precision optoelectronic system components. The most convenient place for its installation is the float-tank operator's post. The measurement block can be placed up to 2 km from the zone of measurements. This distance is determined by the maximum length of fiber-optic cable *2* (limited by optical losses in fiber).

The optical heads *3* (equal to the number of measurement channels *4*) are placed outside on the annealing furnace roof *5* outside the high-temperature zone. This eliminated the need for cooling and complicated thermal protection. Probing radiation is introduced into the annealing furnace via transparent protective windows *6* and is directed perpendicular to the glass ribbon *7*. The optical heads allow for remote probing of the glass ribbon from height up to 3.5 m.

The connecting fiber-optic cable *2* provides for transmission of optical radiation from the measurement block to the optical heads and backwards. The use of the fiber cable

makes it possible to place the measurement block at a distance from the measurement zone and, therefore, to completely remove problems involving its cooling, vibration shielding, etc.

The control block *8* based on a specialized microcontroller or a personal computer provides for fully automated performance of the system displaying data on digital indicators or on the computer display and, if necessary, transmitting data to the controller of the technological process control system. The glass ribbon thickness is monitored in real time simultaneously in all channels.

Main specifications of the system

Absolute error of measuring glass ribbon thickness	5 μm
Resolution	1 μm
Measurement range of glass band thickness	0.1 – 12.0 mm (can be expanded)
Distance between optical head and glass surface	Up to 3.5 m
Site for installing optical heads on glass-production line	From the beginning of annealing furnace to cutting machines
Distance from measurement block to optical head	Up to 2 km
Number of measurement channels	1 – 10 or more
Glass thickness update frequency in all channels	Twice per second
Continuous operation duration	More than 50,000 h

The duration of continuous operation of the system is determined by the service life of the light source (over 50,000 h). The light source can be replaced in industrial conditions. Servicing of the system is reduced to periodical (once in a few months) cleaning of protective peepholes of the optical heads, which can become contaminated in contact with the annealing furnace atmosphere.

It is impossible to measure directly the geometrical thickness of a glass ribbon using the known optical methods. A parameter directly measured in interference measurement is optical glass thickness, i.e., the product of geometrical thickness by the refractive index. The geometrical thickness of the glass ribbon is calculated using the previously determined refractive index (this parameter is not monitored during the measurements). Therefore, a deviation of the refractive index from the previously found value produces an error in determining the geometrical thickness of glass:

$$\delta d = D\delta n,$$

where δn is the deviation of the refractive index from the previously found value and D is the geometrical glass thickness.

Note that sensitivity to the refractive index of glass is not a specific feature of the interference system considered; it is inherent in other optical methods for glass thickness measurement as well, in particular, in triangulation methods.

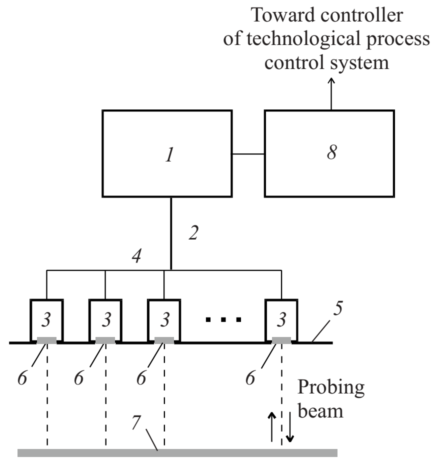

Fig. 3. Block scheme of optical interference system for glass thickness control.

In order to estimate possible errors in determining the geometrical thickness of the glass ribbon related to refractive index fluctuations, refractive indexes were measured in 22 float-glass samples from the Borskii Glass Works produced at different times and taken from different sites across the glass ribbon. It was found that the mean quadratic deviation from the mean value of the refractive index is 2×10^{-4}. The maximum measured deviation from the mean value is 7×10^{-4}, which for 10-mm-thick glass corresponds to an error of 7 μm. Thus, with an accuracy of optical thickness measurement equal to 1 μm, the absolute measurement accuracy of the geometrical thickness of glass depends on fluctuations of the refractive index and is equal to 5 – 7 μm for a glass thickness of 10 mm.

Another source of error in determining geometrical thickness (specific for high-temperature measurements) is related to insufficiently accurate knowledge of glass temperature in the measurement zone. The system measures glass thickness at a hot point, but for process control it is essential to know the thickness of glass after cooling. To determine the thickness of cold glass based on its measurements at a hot point, one should take into account changes in optical glass thickness after cooling. Laboratory experiments indicate that the relative change in the optical thickness of float glass produced at the Borskii Glass Works, as the glass ribbon passes from the measurement point to the cold end of the line, is

$$-1.1438 \times 10^{-5}(T_h - T_c),$$

where T_h is the temperature of glass at the measurement point and T_c is the cold glass temperature.

At $T_h = 500°C$, the temperature correction to the geometrical thickness of 10-mm glass is 75 μm. To provide the absolute accuracy (5 μm) in determining the thickness of 10-mm glass, the glass temperature at the measurement point should be known with an accuracy of about 30°C.

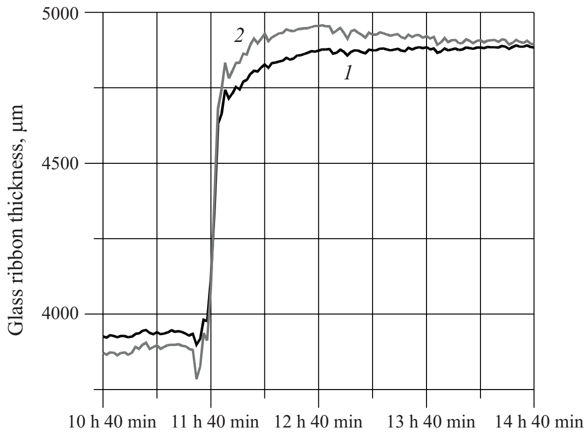

Fig. 4. Plot of glass thickness transition on line LPS-2 along the central channel: *1* and *2*) thickness in the central and extreme left (1.5 m to the left of the ribbon center) channels, respectively.

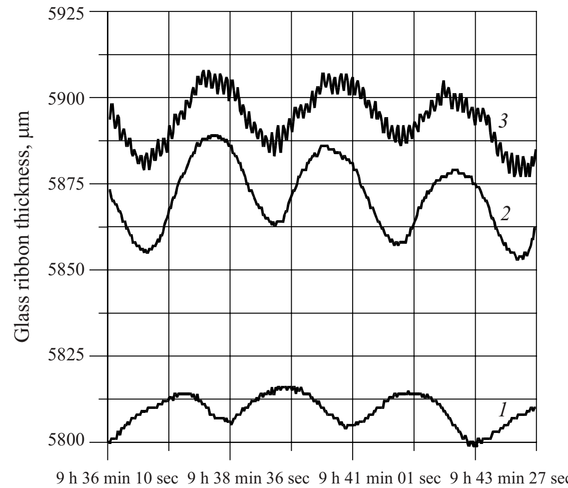

Fig. 5. Plot of transition of glass ribbon thickness recorded by 5-channel system with high time and thickness resolution: *1*) central channel; *2*) right intermediate channel (0.75 m to the right of the ribbon center); *3*) extreme right channel (1.5 m to the right of the ribbon center).

Interference systems for process control of float-glass thickness have been used at the Borskii Glass Works since the beginning of 2000 [3]. The first 3-channel version of the system was installed on the annealing furnace of the first production line for polished glass (LPS-1) in spring of 2000 and after industrial testing in June 2000 was put into service. The system provided for fully automated control of the thickness at three points across the glass ribbon with an accuracy of 10 μm and issuance of data in real time to the control panel and the line controller. Data in the central channel were updated once per 1 sec and data in the lateral channels were updated once per 2 sec. The control protocols were stored on the server of the company computer network. The optical heads were placed on the upper roof of the annealing furnace 20 m from the float-tank. The glass temperature at the point of measurement was around 500°C. For two years the system was continuously operating without long-time stops for repair and servicing and was dismantled in spring of 2002 due to a cold repair of the line.

This system made it possible to significantly increase the line control efficiency, especially during changes in glass thickness. After the system was installed, it became possible to shorten the transitions several times and, accordingly, to decrease glass melt losses. The load on the control-and-measuring system decreased significantly. Continuous indications of the glass ribbon thickness in real time provide place of mind for operators. The existence of measurement protocols improves the responsibility of operators for their performance.

At the end of 2001, an upgraded 5-channel interference PC-controlled system for glass thickness control was installed on the second new float-glass line at the Borskii Glass Works. The measurement block and the controlling computer are installed in the float-tank operator' room. The optical heads are installed on the annealing furnace roof 20 m from the float tank (Fig. 2). The distance between the optical head and the glass ribbon is 1.1 m. The absolute accuracy of measuring the ribbon thickness is within the limits of 5 μm, and the resolution is 1 μm. The measurement data are displayed on the computer display, stored on the hard disk, and transmitted to the line controller. Update of glass thickness data in all five channels occurs each second. In March 2001 the system was put into service after industrial testing.

Figure 4 shows the plot of transition from 4-mm glass to 5-mm glass recorded by the new 5-channel system. It can be seen that the system provides for continuous measuring, even at moments of the fastest change in the glass ribbon thickness.

Owing to improved resolution and faster performance, the new version of the system makes it possible to monitor fine nuances of the glass production process, which used to pass unnoticed before. Figure 5 shows glass ribbon thickness plots in three channels with time resolution of 1 sec and thickness resolution of 1 μm.

All channels register quasiperiodical fluctuations in glass ribbon thickness with a period of slightly over 2 min and an amplitude of 20 μm. This correlates with a wave on the upper surface of glass with a period of 6 m and an amplitude about 20 μm. The outer channel shows ripples with a spatial period about 30 cm and an amplitude around 5 μm. The wavy surface of glass accounts for discrepancies between the control system measurements and the system data, which sometimes occur. The origin of these waves is not yet clear. Thus, technologists have the possibility of observing processes that used to be inaccessible for observation.

In August 2002, after a cold repair, an upgraded version of 5-channel interference system for monitoring glass thickness operated by a special microcontroller was installed on the float-glass production line at the Borskii Glass Works. The measuring and the controlling blocks are placed in the float-tank operators' room. The optical heads are installed on

the annealing furnace roof 20 m from the float-tank (Fig. 2). The distance between the optical head and the glass ribbon is 1.1 m. The absolute accuracy of measuring glass ribbon thickness is within the limits of 5 μm, and the resolution is 1 μm. The measurement data are displayed on the external indicator dial and transmitted to the line controller. The data in all five channels on glass thickness are updated each second. In October 2002 the system was accepted for service after industrial testing.

The three-year experience of using interference control systems for glass thickness has proved their high reliability and efficiency and has opened up new opportunities in controlling the process.

Based on the system described above, a new system with a scanning head was designed at the end of 2002 to control the cross-section profile of glass ribbon thickness at the exit from the annealing furnace in front of the first glass-breaking machine. The system is currently being tested. Its specifications are as follows: measurement accuracy 5 μm, thickness resolution 1 μm, measurement update 10 times per 1 sec. The system can measure thickness of glass with an angle up to 0.5° without losing accuracy, which is better by an order of magnitude than the analogous parameter in contemporary triangulation systems and makes it possible to measure glass thickness in the immediate vicinity (about 20 mm) of the trace of the edge-forming machine. Figure 6 represents the cross-section profile of glass. It is apparent that continuous monitoring of the glass ribbon thickness in the hot zone makes it possible to maintain thickness close to the lowest rated value, whereas deviations in thickness across the ribbon width do not exceed 0.07 mm.

As a consequence of laboratory experiments, new possibilities for application of interference diagnostic systems in the glass industry have been identified. An example is measuring the thickness of layers in laminated glasses, such as triplex. Triplex glass can be measured using the same equipment as measuring float-glass thickness; it is just software that has to be adjusted, and in some cases the design of optical heads has to be modified. Another promising use for the new measuring systems is measuring the size of glass articles of complex shape, such as measuring the thickness of bottle walls and bottom or thickness of thin glass tubes. Such measurements were demonstrated in laboratory simulations of the interference control system.

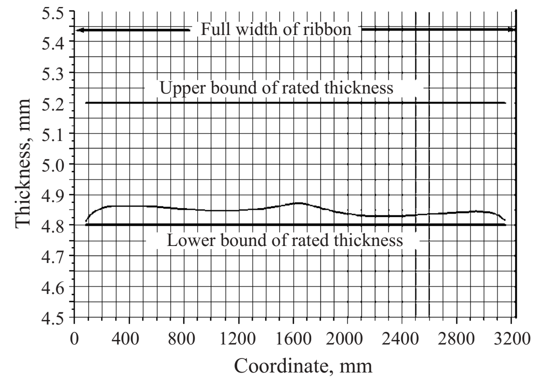

Fig. 6. Cross-section profile of glass ribbon on production line LPS-1. The boundaries correspond to full width of the ribbon.

It is also interesting to shift the glass thickness control zone to a higher-temperature area, i.e., to the float-glass tank. There are no fundamental obstacles to doing this, since none of the instruments is located directly in the high-temperature zone and none experience the effect of high temperature, whereas the possibility of probing a glass ribbon from a distance up to 3.5 m was experimentally tested. The interference system with gage heads located above the glass ribbon outside the high-temperature zone provides for unique control possibilities in the float tank, where optical access from below is impossible.

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REFERENCES

1. M. Marinelle, "Float and automotive glass on-line quality control," *Glass-Technol. Int.*, Issue 3, 7 – 11 (1997).
2. D. Buelens, "Float glass thickness measurement new system," *Automotive Glass*, No. 2, 37 – 40 (1990).
3. M. A. Novikov, A. D. Tertyshik, V. V. Ivanov, et al., "New optical method for remote diagnostics of glass components," in: *Glass Processing Days: Conf. Proceedings*, Tampore (2001), pp. 256 – 260.